Growth and Device Strategies for AlGaN-Based UV Emitters

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Introduction

- The AlGaN alloy system is very promising for UV emitters: E_g = 3.4 to 6.2 eV (all direct), or λ=200 nm to 365 nm
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- Challenges presented by this system include:
  - Low recombination efficiency due to strong polarization fields in quantum wells
  -
  - Lack of carrier localization (as in InGaN QWs) before non-radiative recombination occurs at threading dislocations
  -
  - Low electrical activation in p-GaN, as well as high contact ρ
  -
  - Growth problems: rough surfaces, high dislocation densities, strain-induced cracking

Progress in AlGaN-Based UV LEDs

- **Meijo:** GaN/AlGaN DH: 1.5 % EQE @ **370 nm**
-
- **Sandia**: **GaN** MQW, EQE < 1% @ **353.6 nm** (13 μW, 20 mA)
  - limited by self-absorption and unoptimized light extraction
-
- **NTT**: **$Al_{.08}$GaN** MQWs, λ = **346 nm**, constant λ to I = 800 A/cm^2
-
- **Nichia**: **InGaN/AlGaN** DH, 7.5% EQE @ **371 nm**, 5mW power
  InGaN SQW, 10% EQE @ **380 nm**, 7 mA

- **RIKEN/Waseda**: **$Al_{.03}$GaN** MQWs, λ down to ~**335nm**
-
- **Cree Lighting Company**: InGaN MQW with 32% EQE
  @ **390 nm** (21 mW power, 20 mA).
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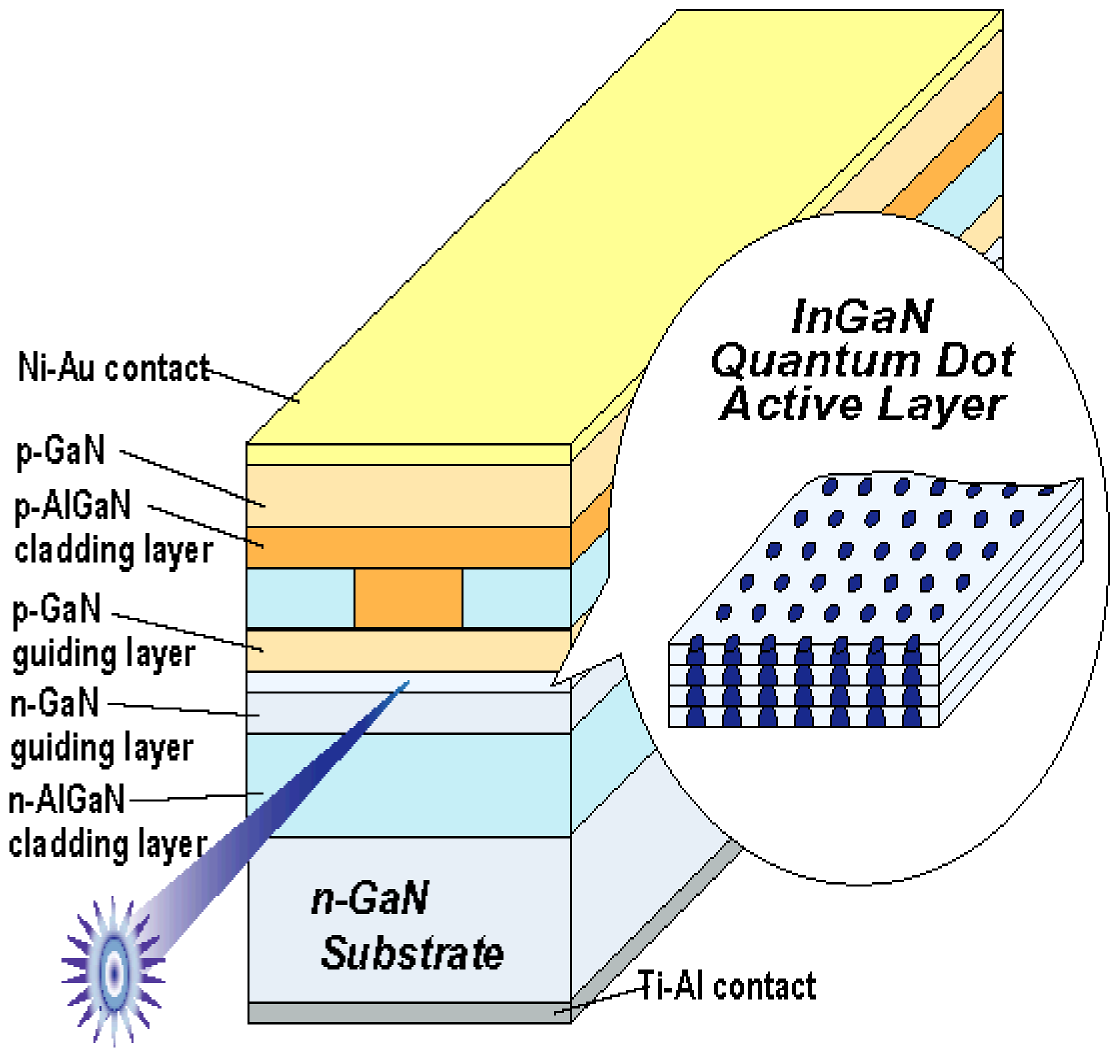
InGaN Quantum Dot Laser Diode



GaN: Wide Band Gap

- QDs with deep potentials
- **Low thermal emission from QDs to barrier**

GaN Substrate:

- Low dislocation density
- **Few non-radiative recombination centers**

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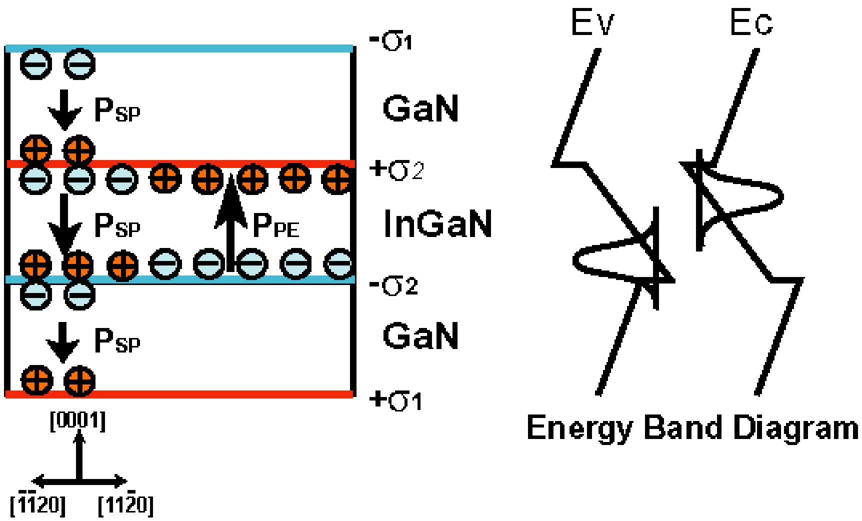
Quantum-confined Stark Effect (cont.)

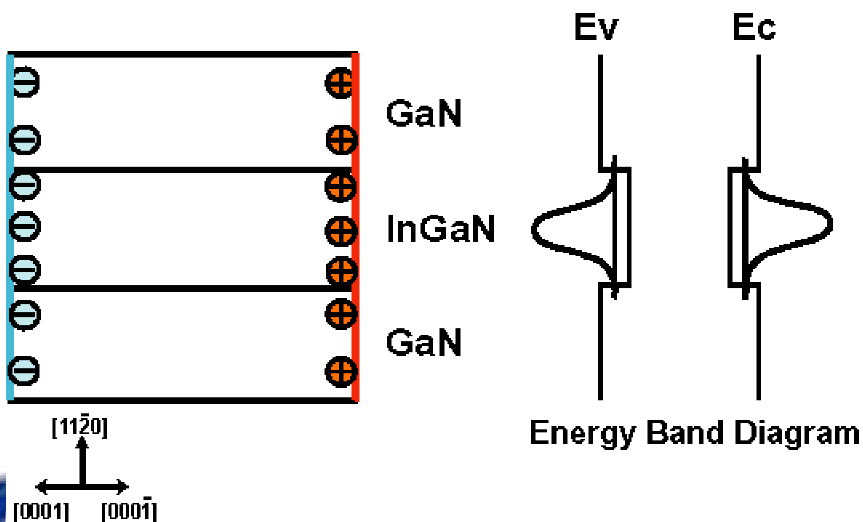
- QCSE becomes worse with increasing well width, and causes red shift in emission
-
- Avoiding the QCSE:
-
    - Induce growth in non-polar GaN directions such as $[1\bar{1}00]$, on substrates such as $LiAlO_2$ [à la Paul-Drude-Institut, Berlin, Germany]
    -
    - Homoepitaxial Growth on non-polar GaN substrates derived from **bulk** crystal growth
    -
    - Growth of lattice-matched quaternary $Al_xIn_yGa_{1-x-y}N$ compositions

Polarization Effects

on C Plane (Ga Face)



on A Plane



Spontaneous and piezoelectric polarization cause:

1. band bending
2. charge separation in QW

- **Red shift of the emission**
- **Low recomination efficiency**
- **High threshold current**

Growth on A-, M-plane GaN will solve these problems

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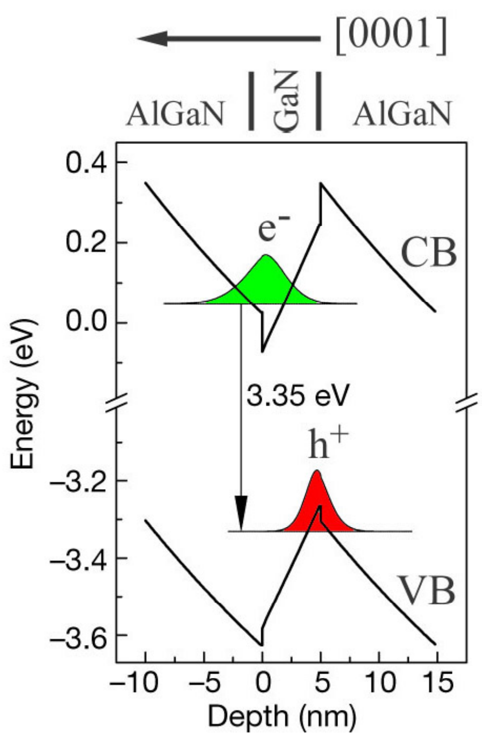
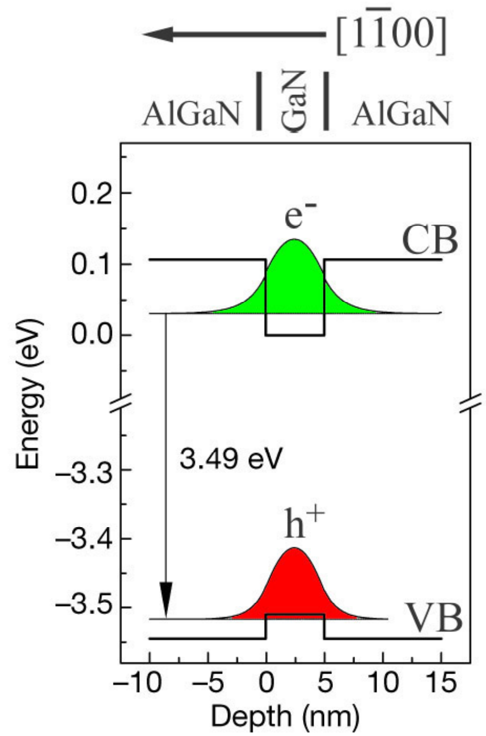
Quantum-confined Stark Effect

- QCSE: spatial carrier separation induced by polarization fields

Polar



Non-Polar



Lower recombination efficiency in GaN QWs on polar layers (left) vs. non-polar layers (right)

(after Waltereit et al., Nature ***406****, 865 (2000))*

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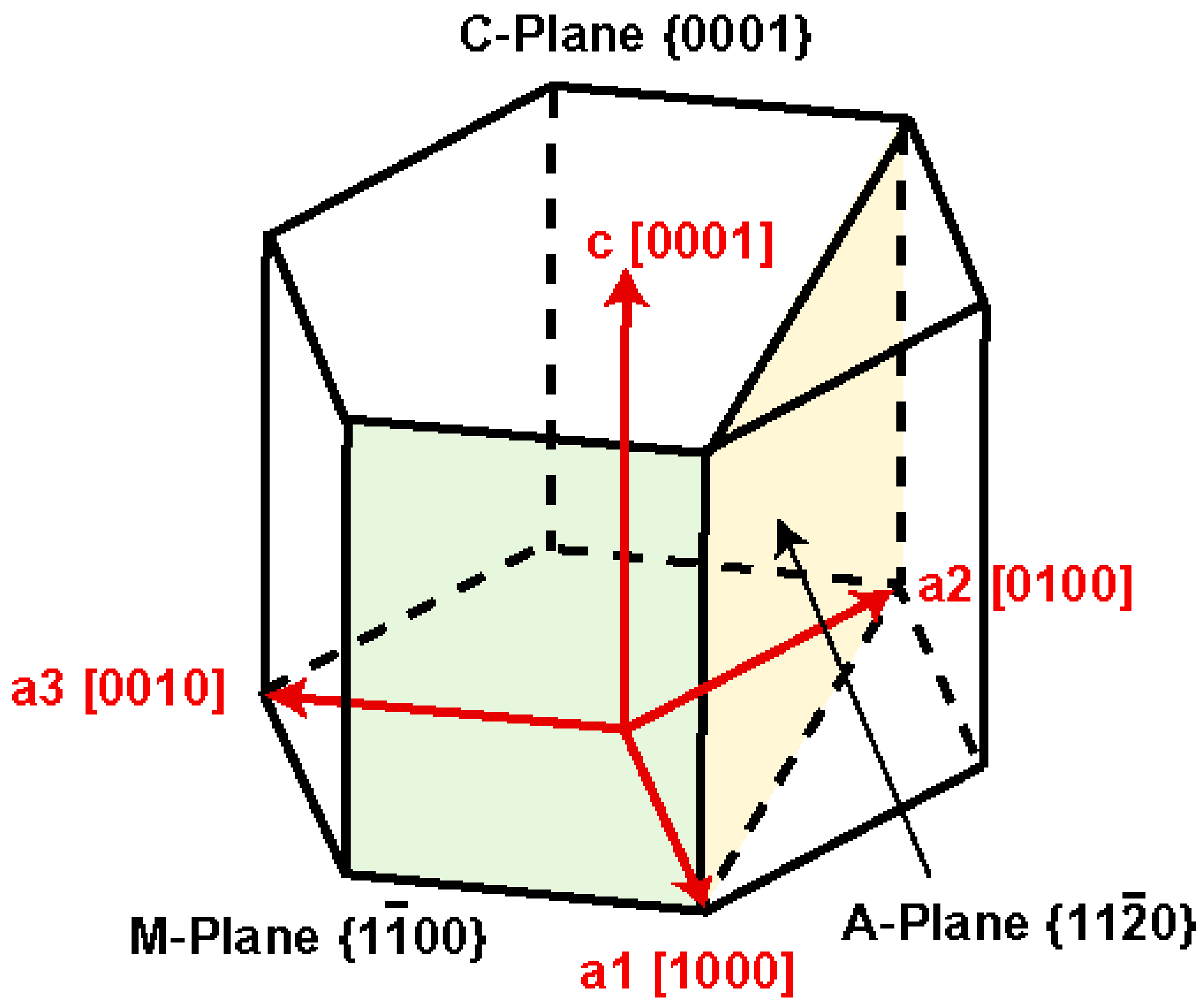
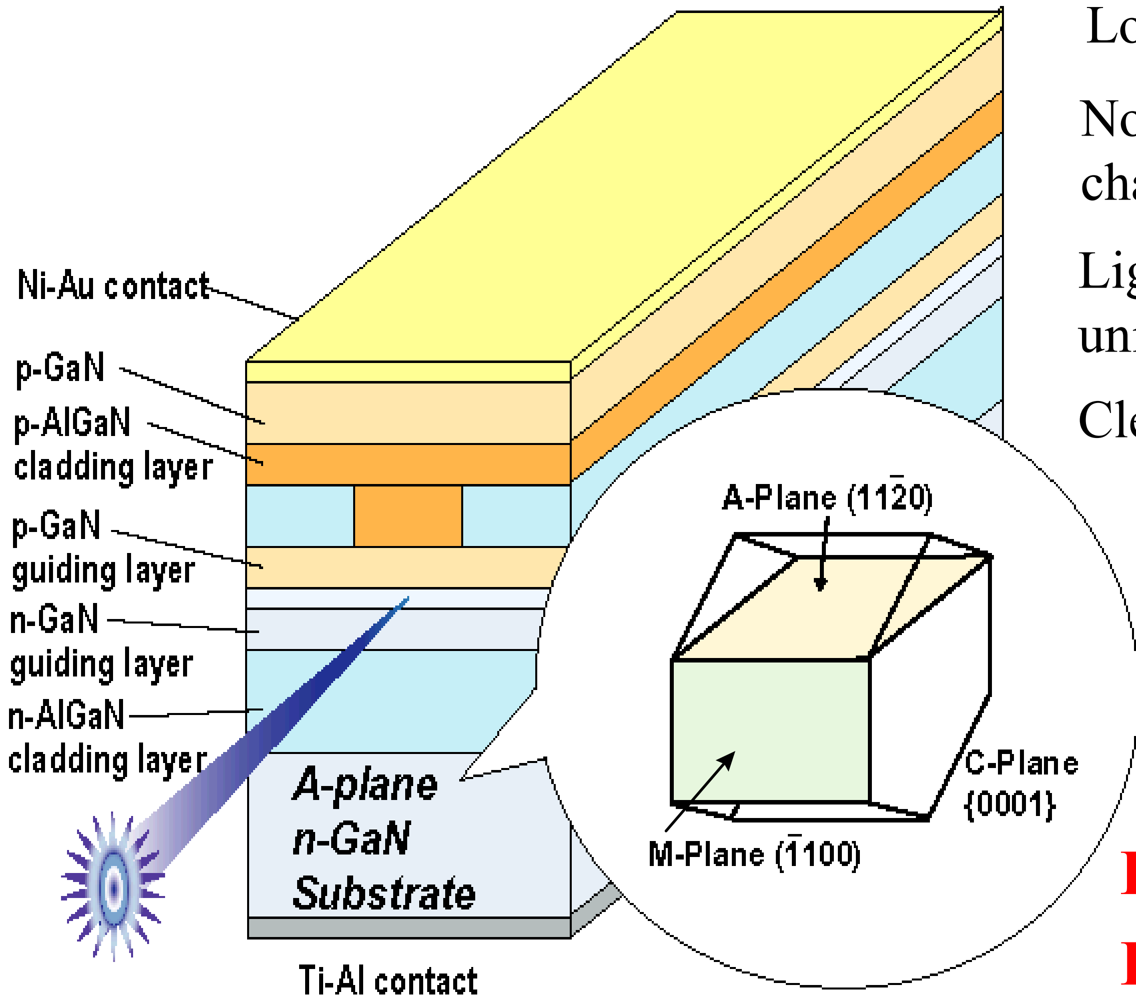
Crystal Structure of GaN



InGaN Laser Diode on A-plane GaN



Low dislocation density

No polarization-induced charge separation in QWs

Lighter hole mass due to uniaxial strain

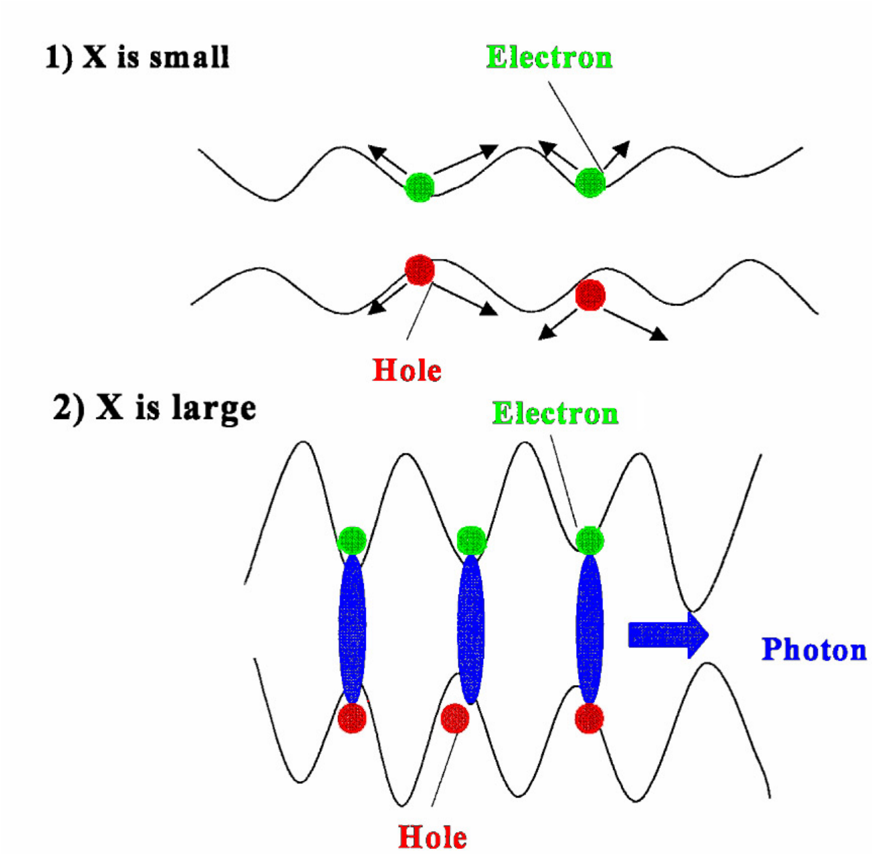
Cleaved mirror with M-plane

Low threshold current

High reliability

Carrier localization in InGaN QWs

- Compositional inhomogeneity in InGaN leads to ‘clustering’:



Carriers gather in areas of lower bandgap and recombine radiatively

(after S. Nakamura, IEICE Trans. Electron. ***E83-C****, 539 (2000))*

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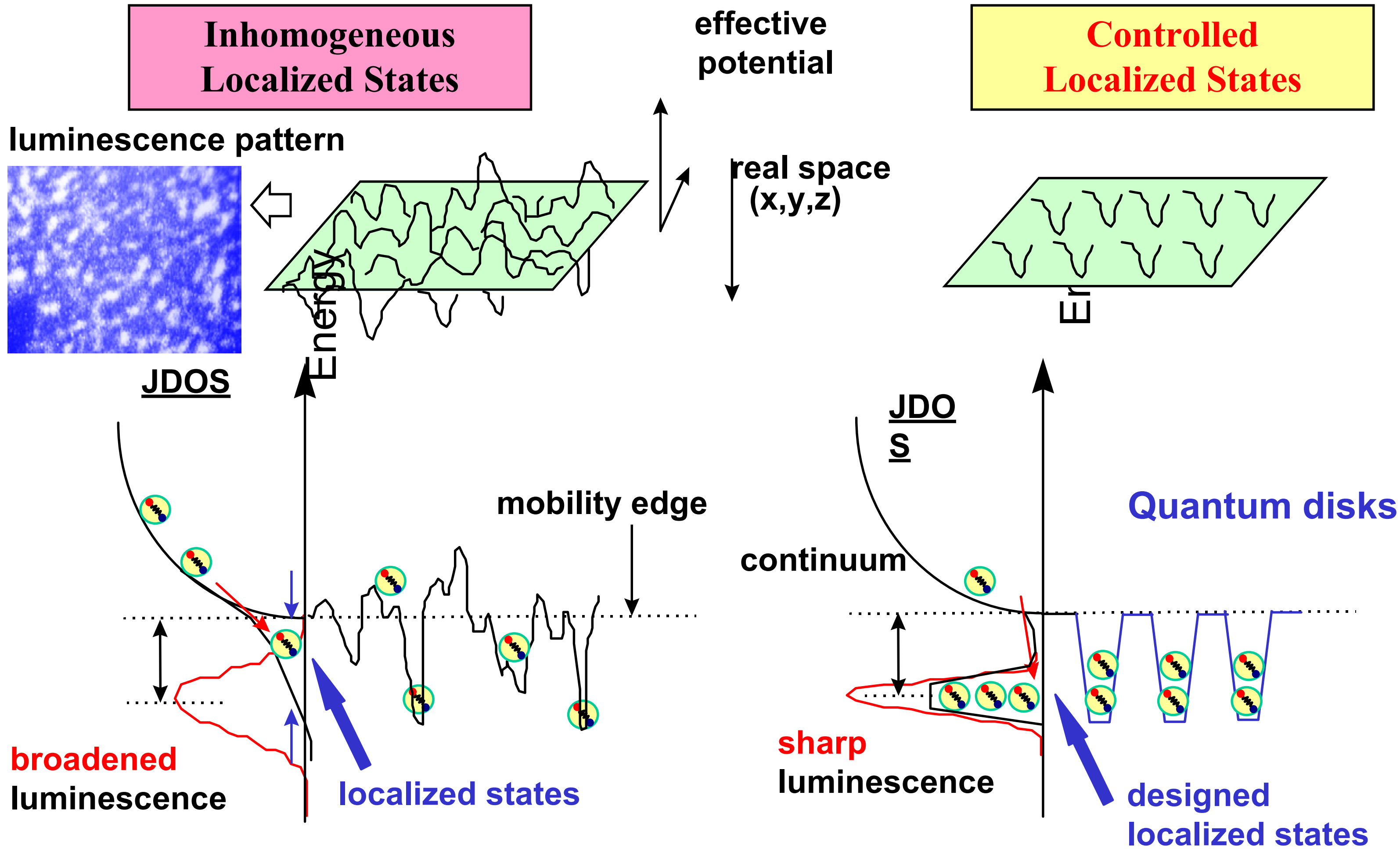
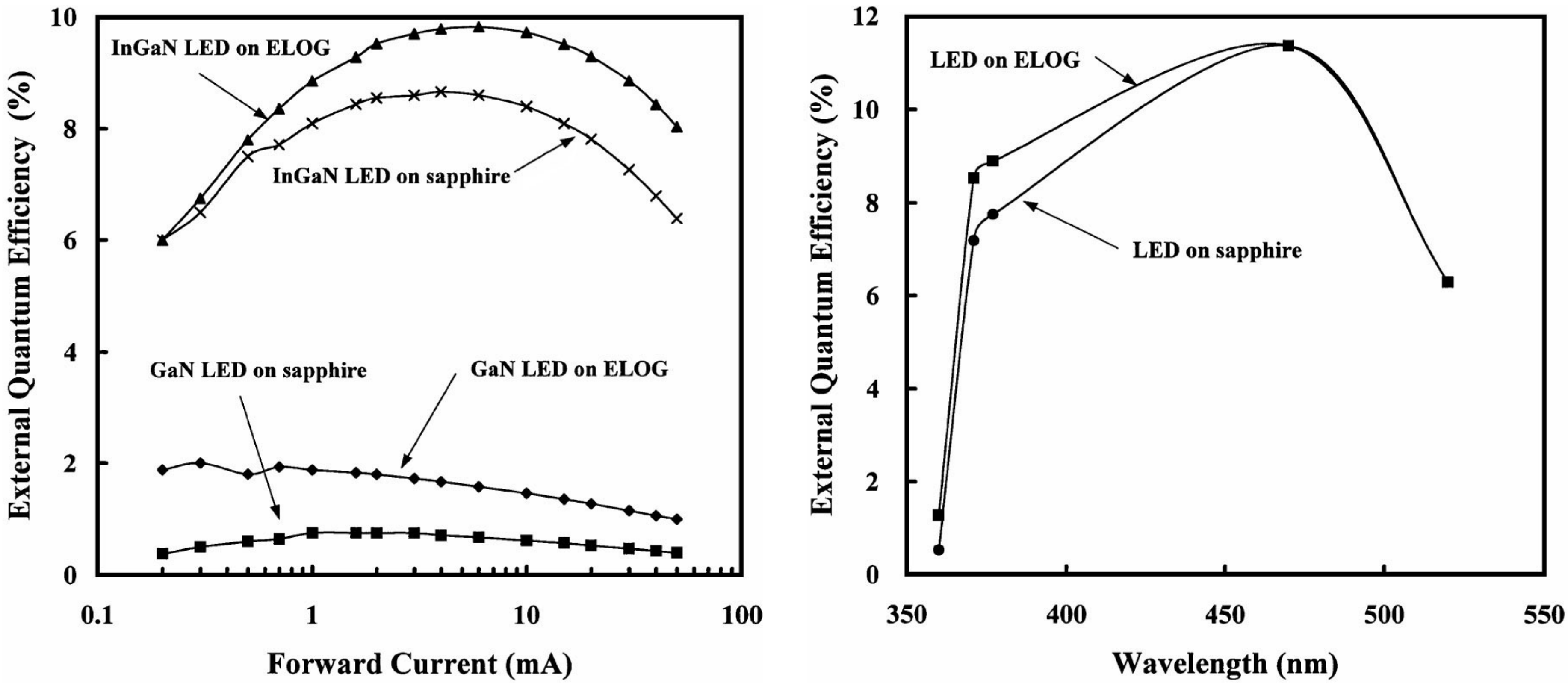
Joint Density of States in nanometer-scale inhomogeneous materials



Designed localized states have smaller DOS (population inversion easier) and produce giant gain due to many-body effect including EXCITONIC gain

Lowered Quantum Efficiency in GaN QWs

- Unlike InGaN QWs, (Al)GaN QWs do not exhibit compositional clustering and therefore have lower EQE:



(after Mukai and Nakamura, Jpn. J. Appl. Phys. ***38*** *5735 (1999))*

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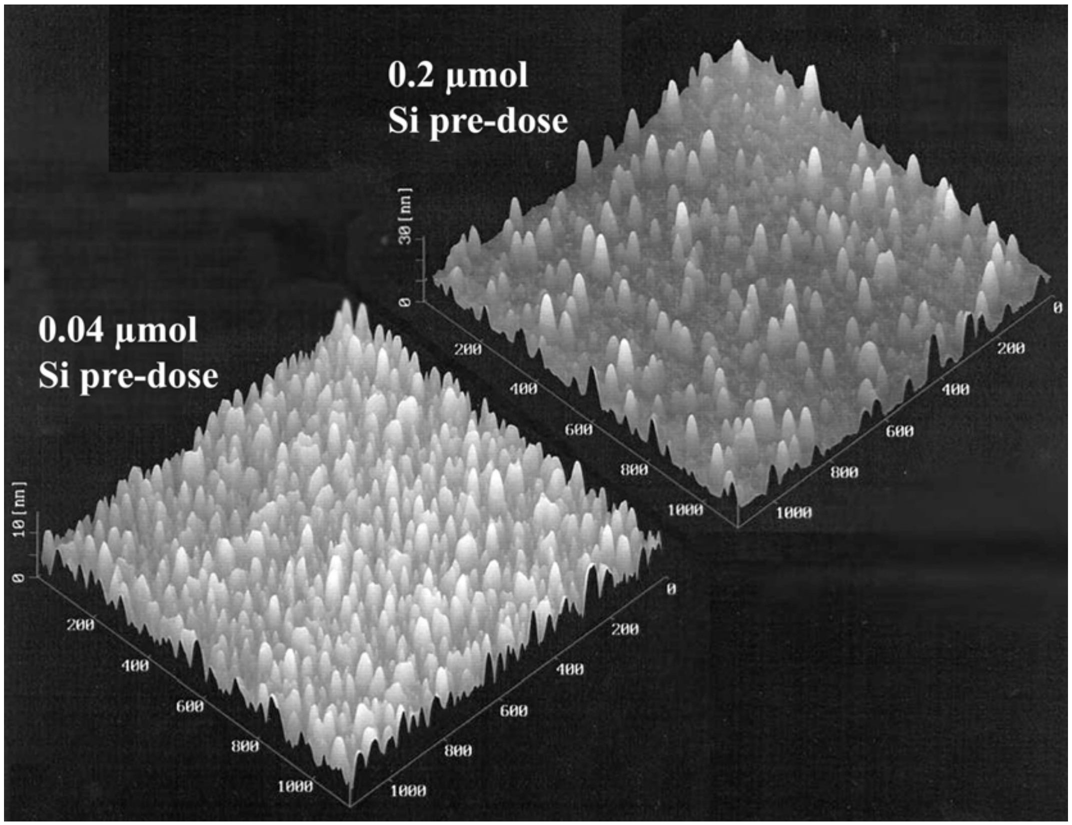
Qdots for Carrier Localization

- Quantum dots may be utilized to capture carriers that would otherwise migrate to dislocations

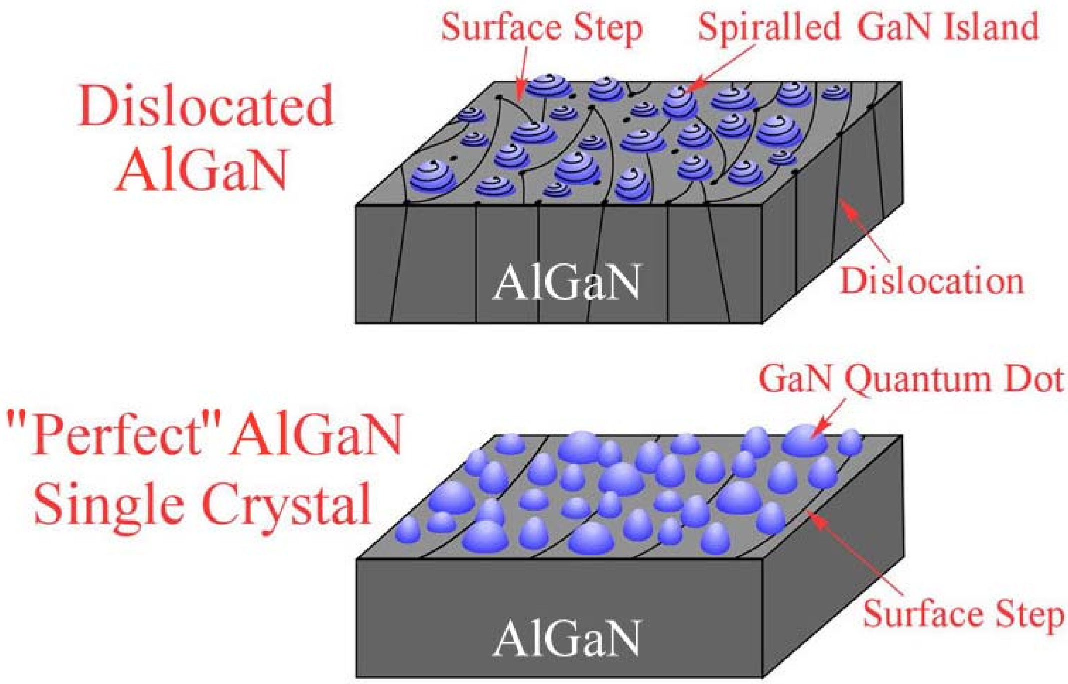


$Al_{.05}GaN$ islands on **$Al_{.4}GaN$** cladding layers: island size and distribution strongly depends on Si pre-dose

(after Hirayama et al., MRS Internet J. Nitride Semicond. Res. 4S1, G9.4 (1999))

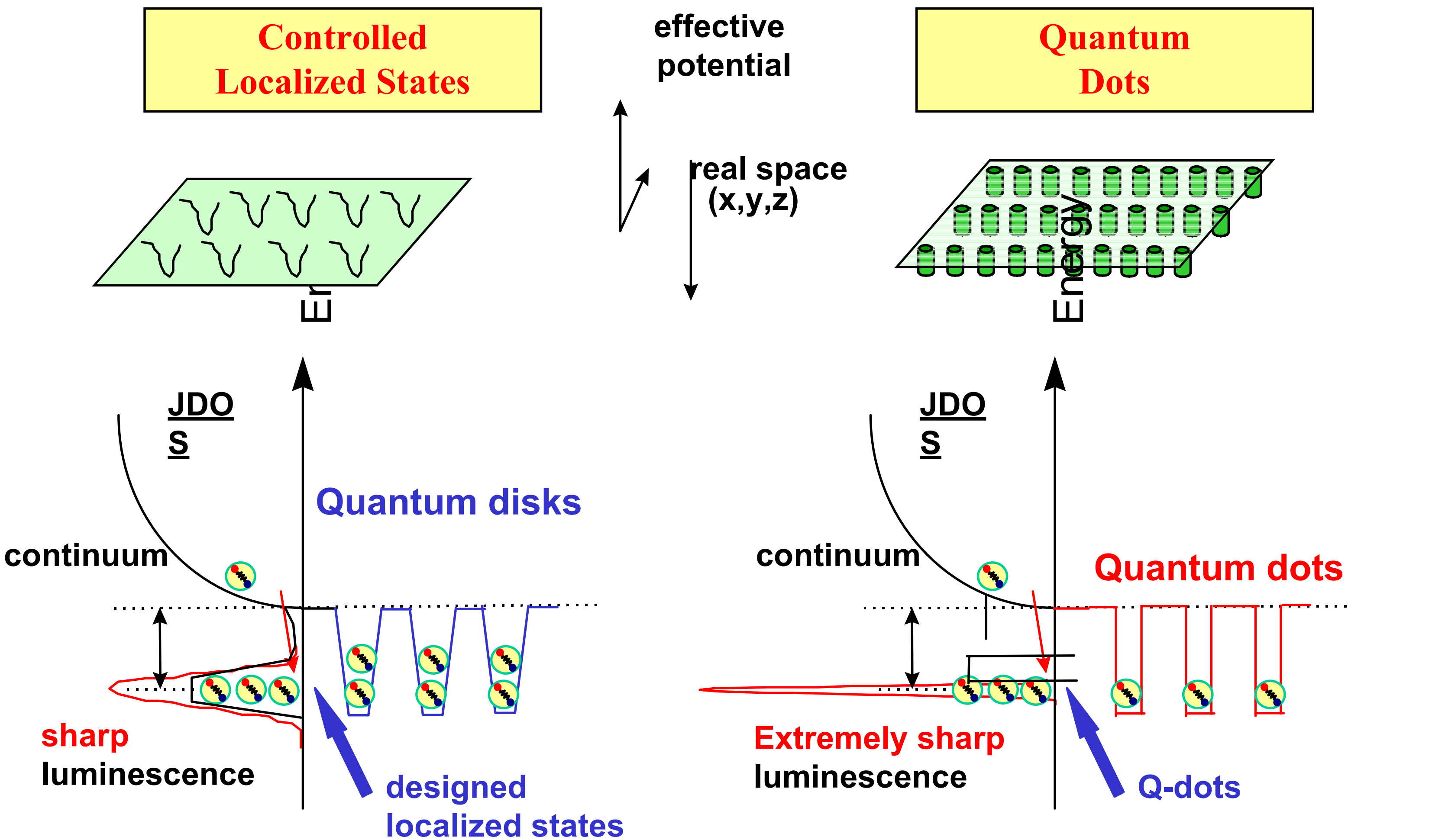
Qdots for Carrier Localization (cont.)

- Quantum dot size distribution and density will likely also depend on morphology of underlying layer:



Areal density of threading dislocation terminations may influence GaN island growth mode on AlGaN 'template'

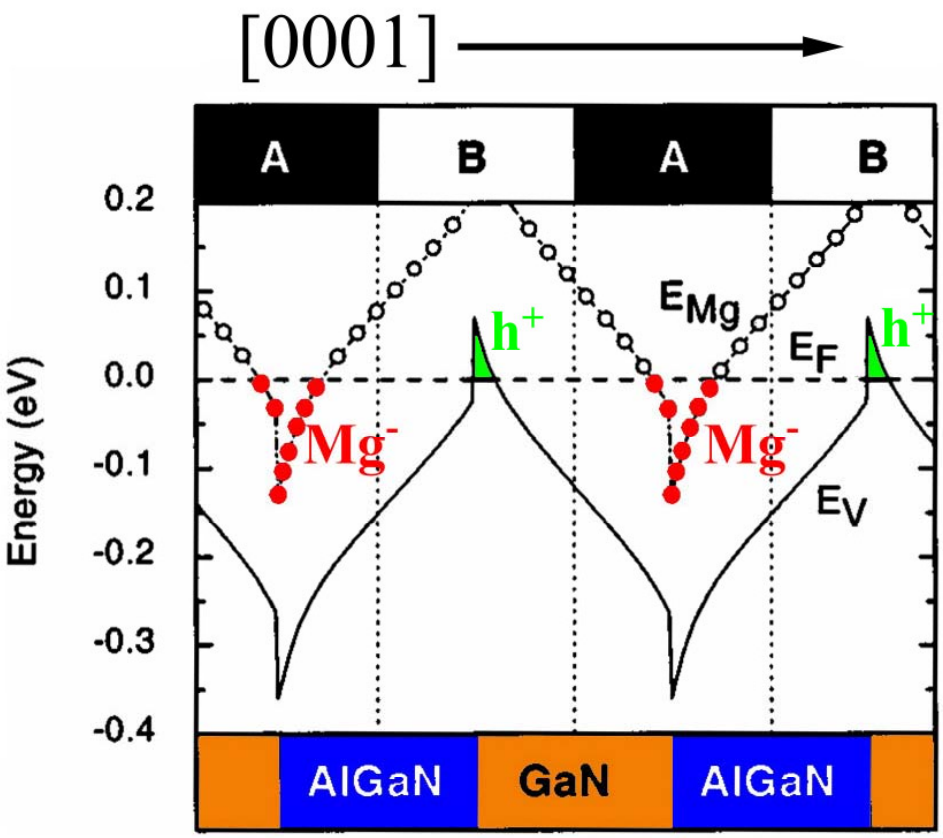
Designed Quantum Dots



Quantum dots have smaller but definite DOS (population inversion easier) and produce giant gain

Superlattices for Enhanced Hole Concentration

- p-AlGaN/GaN SLs enhance hole concentration by ~ 10 times



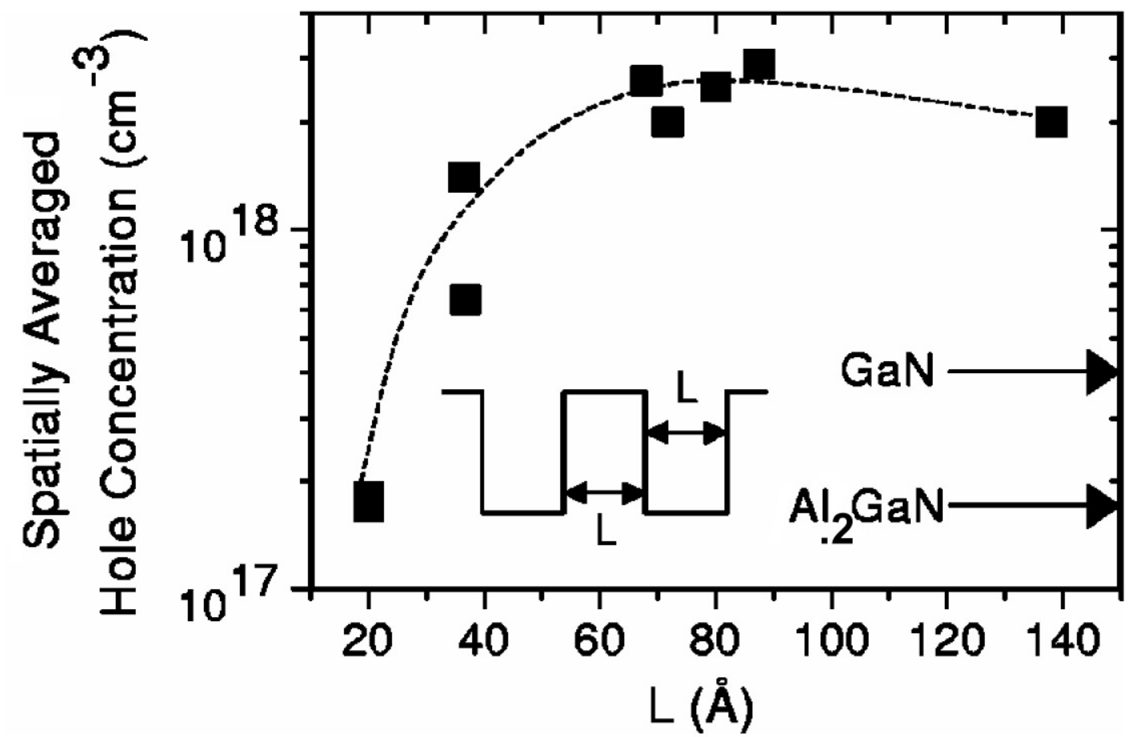
Mg acceptors below the Fermi level ionize and holes accumulate at AlGaN/GaN interfaces

"A" Regions: doping desirable
"B" Regions: doping undesirable

(after P. Kozodoy et al., Appl. Phys. Lett. ***75****, 2444 (1999))*

SLs for Enhanced Hole Concentration (cont.)

- Optimum period of superlattice must be found, which is dependent on Al content

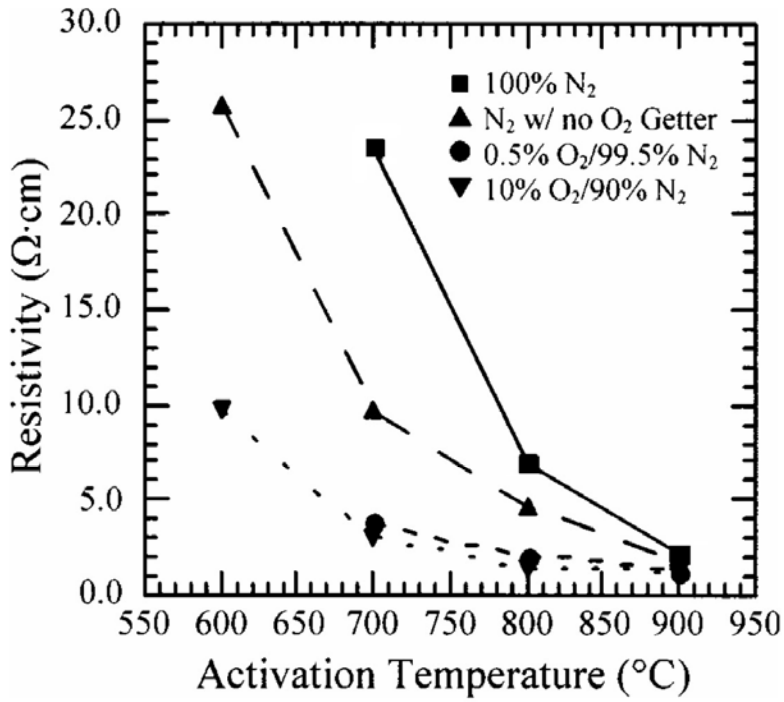


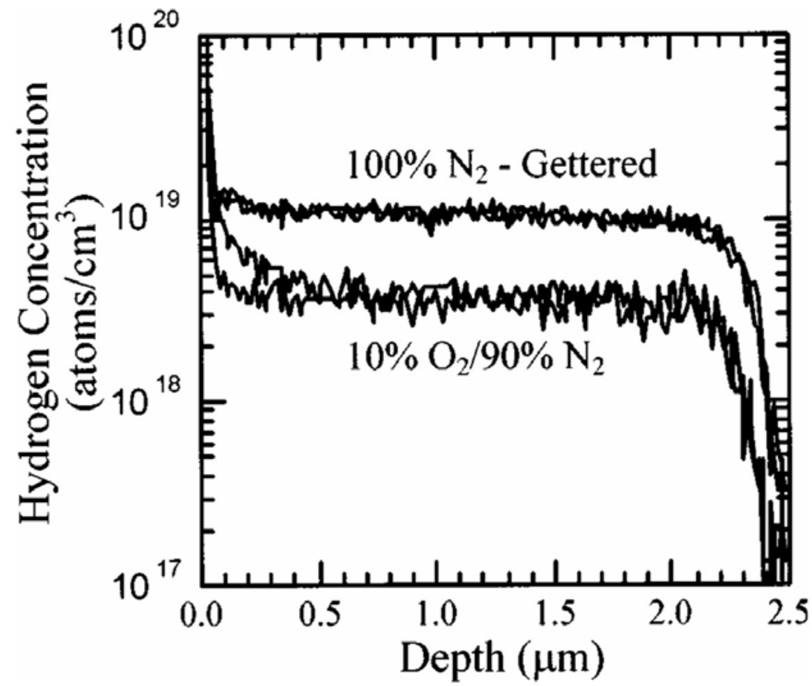
At higher SL periods, space charge screens polarization field across the GaN wells

(after P. Kozodoy et al., Appl. Phys. Lett. ***74****, 3681 (1999))*

P-GaN Annealing

- Effectiveness of p-GaN activation anneal (pre-metallization) depends on gas ambient:



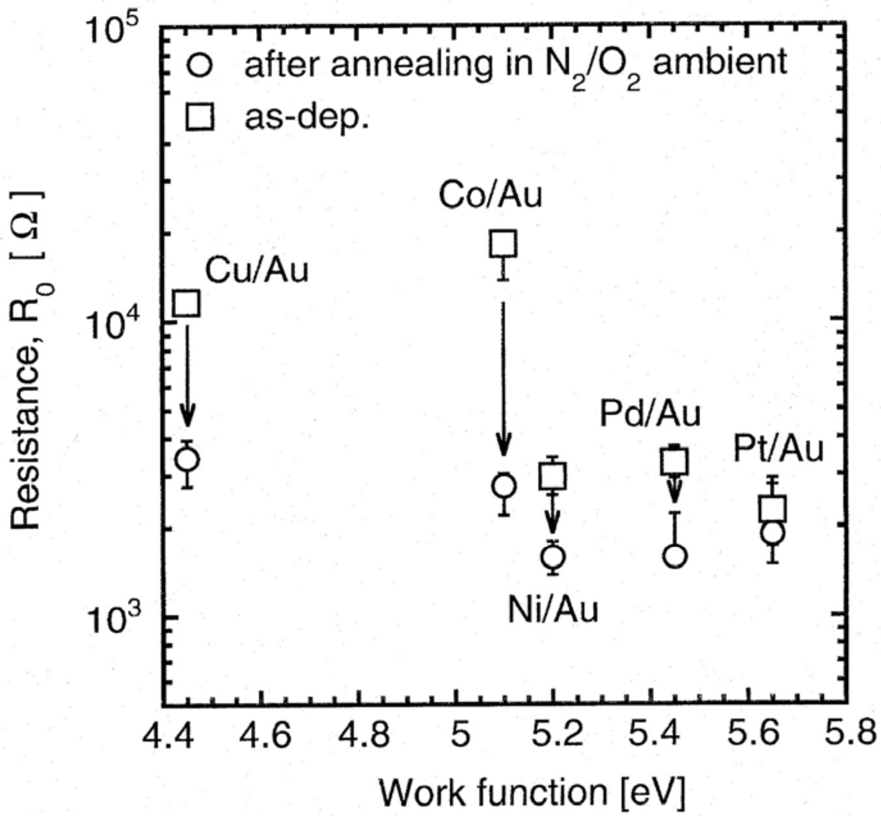


Oxygen appears to be an effective getter for H in Mg-doped GaN

(after Hull et al., Appl. Phys. Lett. ***76****, 2271 (2000))*

P-GaN Contact Metals

- p-GaN contact metal anneal: both annealing temperature and ambient are important

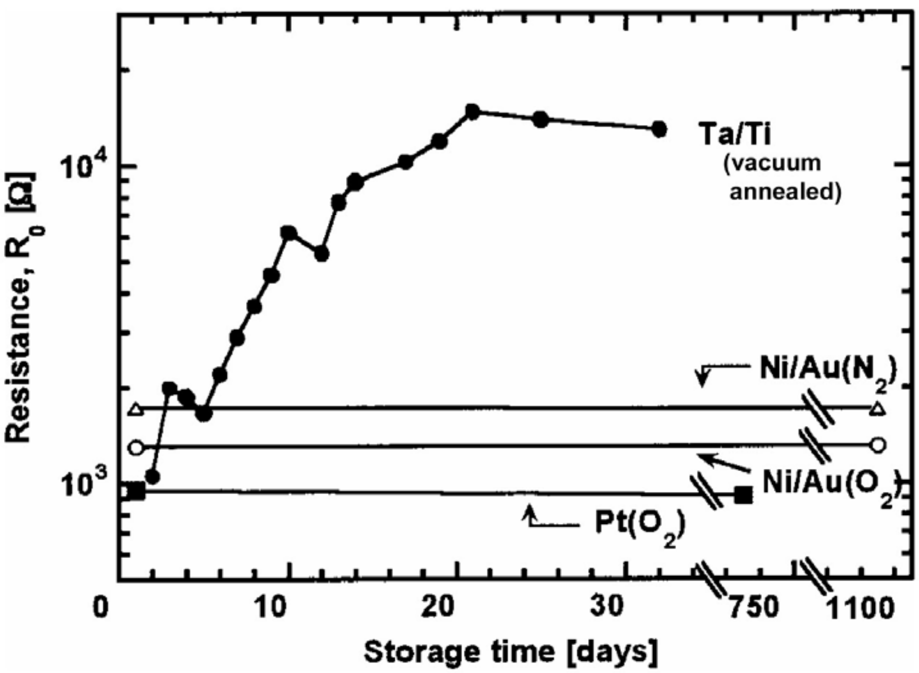


Resistance of all contacts annealed at 500°C in N_2/O_2 decreases

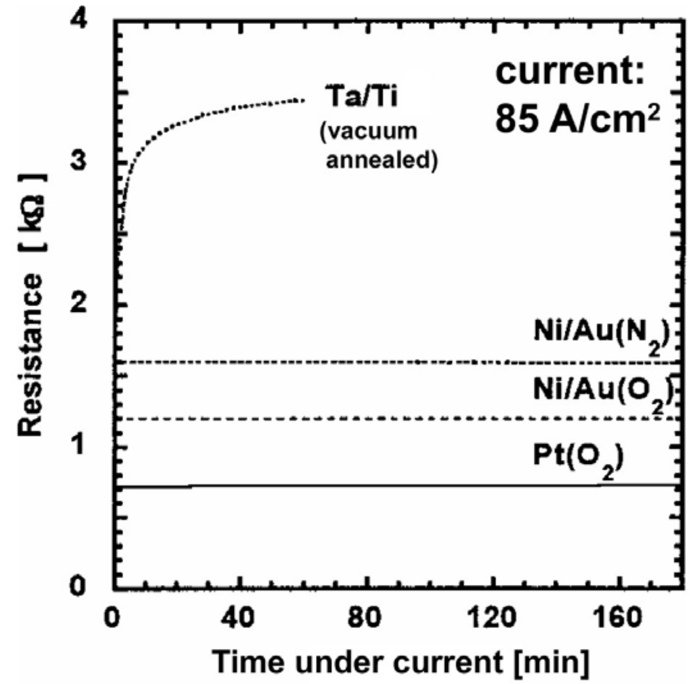
(after Koide et al., J. Electron. Mat. ***28****, 341 (1999))*

P-GaN Contact Metals (cont.)

- Contact stability during storage and operation must be considered:



Vacuum -annealed Ta/Ti contacts have low R, but are not stable over time.



R of Ta/Ti increases rapidly during current injection, but is recoverable with another vaccum anneal.

(after Arai et al., J. Appl. Phys. ***89****, 2826 (2001))*

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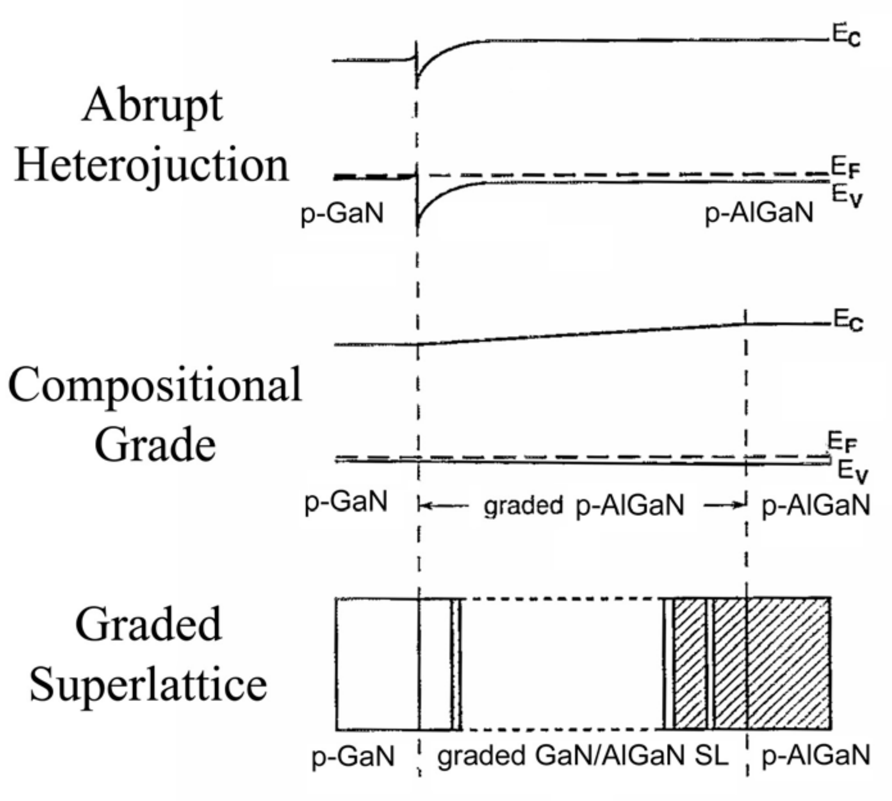
Graded p-type Contact Layers

- p-GaN is often used as contact layer; grading to AlGaN/GaN SL avoids abrupt valence band hole barrier

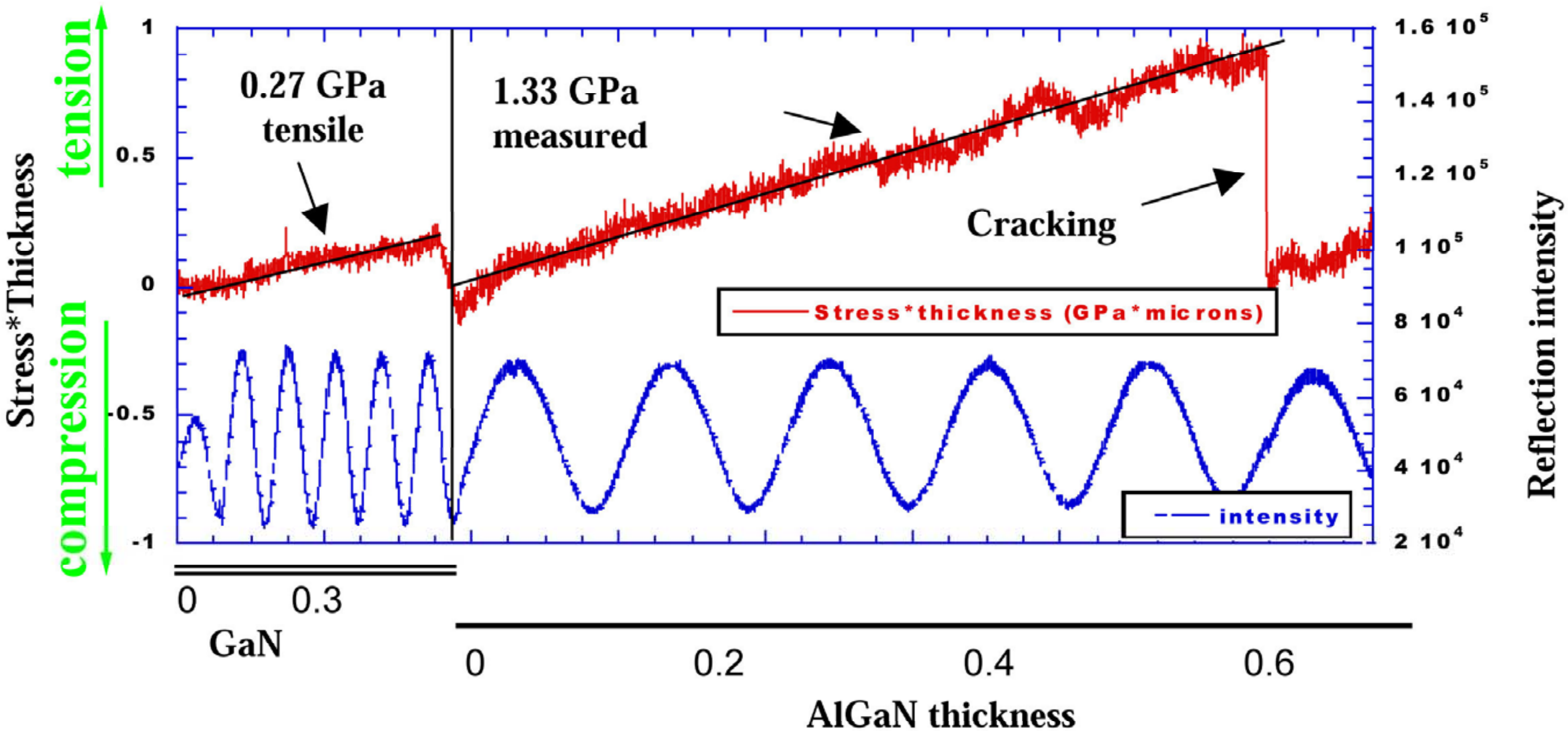


e.g. grade χ_{Al} in barriers of a GaN/AlGaN doping superlattice

(adapted from Fan et al., Appl. Phys. Lett. ***61****, 3160 (1992))*

AlGaN growth: cracking due to tensile stress

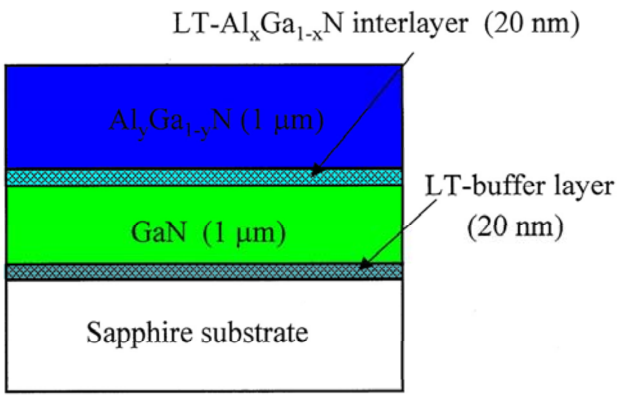
- AlGaN on GaN: tensile stress may cause cracking during growth, as observed *in situ* with multibeam laser monitoring



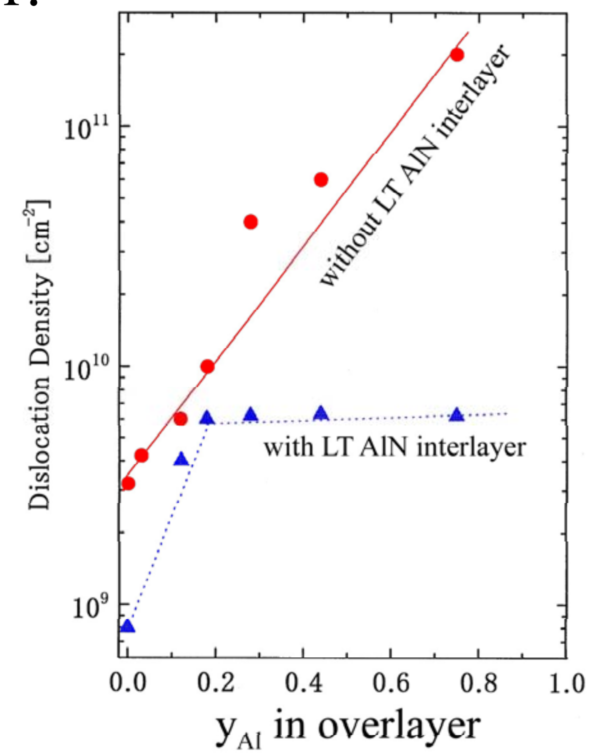
(after J. Han et al., MRS Internet J. Nitride Semicond. Res. 4S1, G7.7 (1999))

Low-T Interlayers for AlGaN Stress Control

- LT Al(Ga)N interlayers may lower stress as well as dislocation density in the overlying AlGaN layer:



Al content in interlayer (x_{Al}) must be higher than that in overlayer (y_{Al})

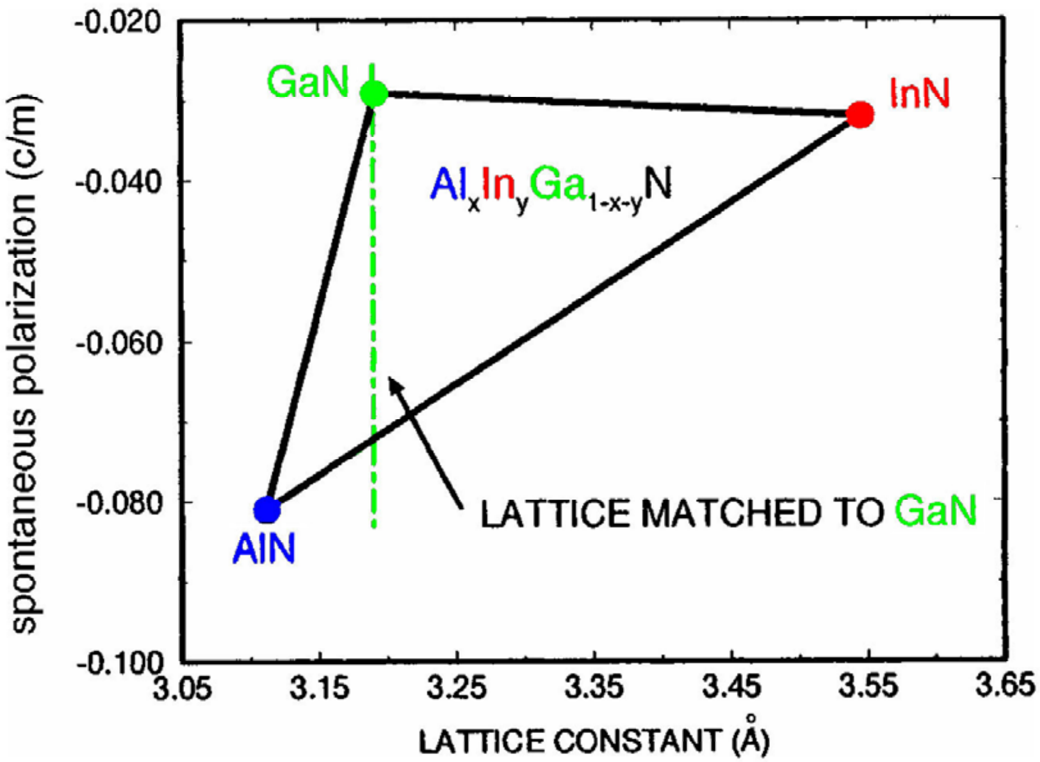


TD density in AlGaN overlayer is nearly independent of Al content when it is grown on an AlN interlayer

*(after Kamiyama et al., J. Cryst. Growth **223**, 83 (2001))*

Polarization Control in Quaternaries

- Quaternary compositions control strain, and therefore piezoelectric polarization



Although lattice matching controls piezolectric effect, spontaneous polarization remains

*(after Fiorentini et al., Phys. Rev. B **60**, 8849 (1999))*

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Summary/Conclusions

- Carrier localization, *e.g.* in (Al)GaN Qdots: increase carrier recombination efficiency
-
- Polarization control: either through non-polar growth or use of quaternary compositions
-
- Environmental stability of low-ρ contacts such as Ta/Ti needs to be increased
-
- Use of graded contact layers: "smooth" energy transition for holes
-
- Low-T Al(Ga)N interlayers for stress control of overlying AlGaN
-
- Lower dislocation densities needed: LEO or growth on 'bulk' homoepitaxial substrates

Lateral Epitaxial Overgrowth (LEO) of GaN

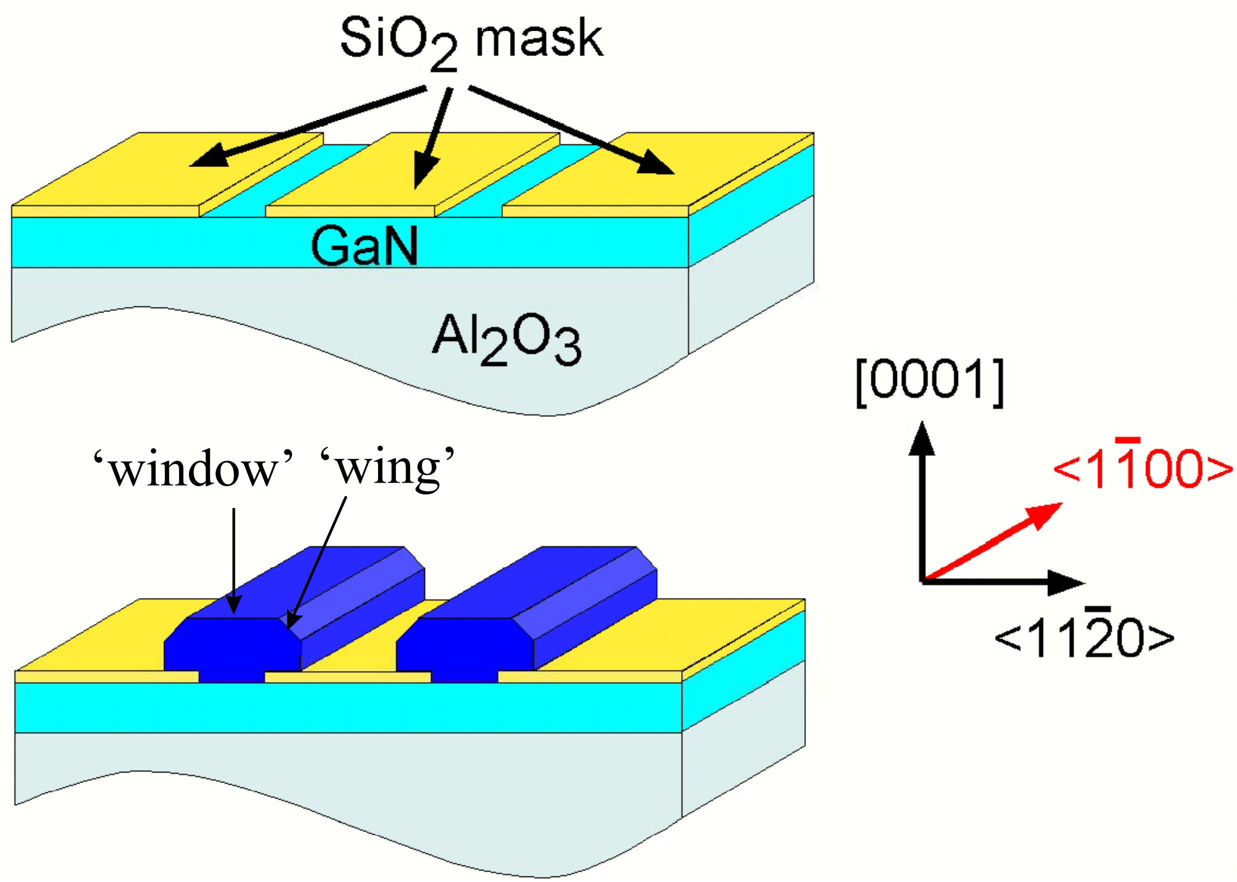
- Strategy: selectively mask a GaN film; regrow through openings and over mask

Patterning

PECVD
Wet etching
5 μm stripes
spacing 5-500 μm

LEO growth

LP-MOCVD
TMG, NH_3
5 μm/hr nom.
1015-1100°C



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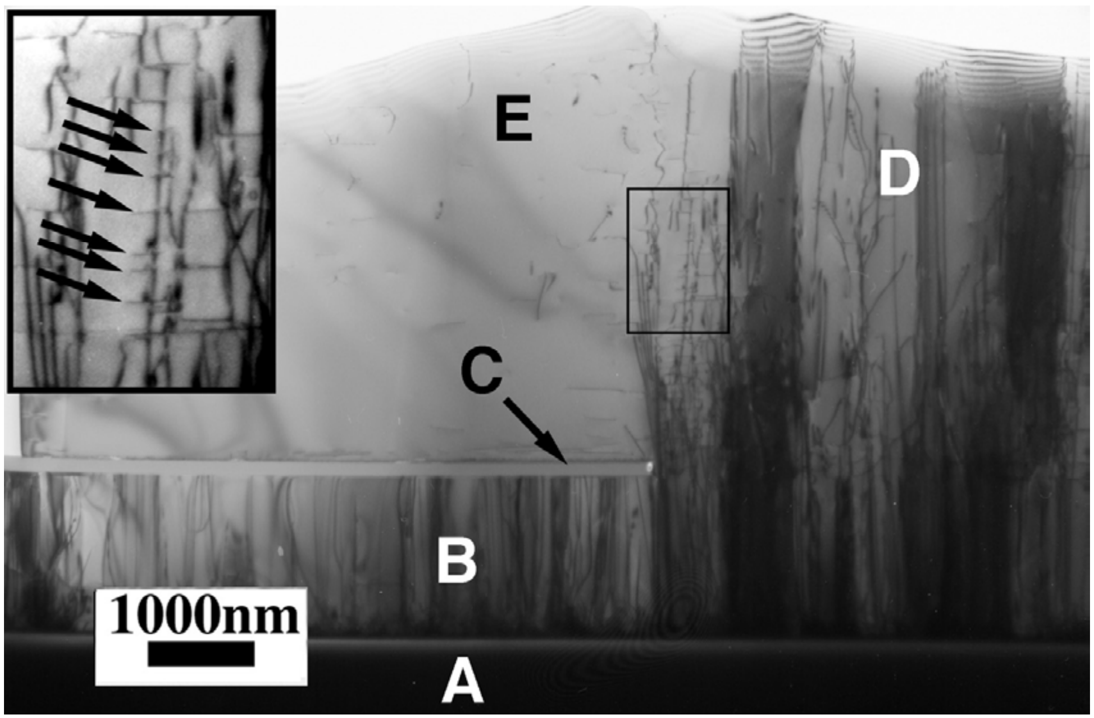
Lateral Epitaxial Overgrowth (LEO) of GaN

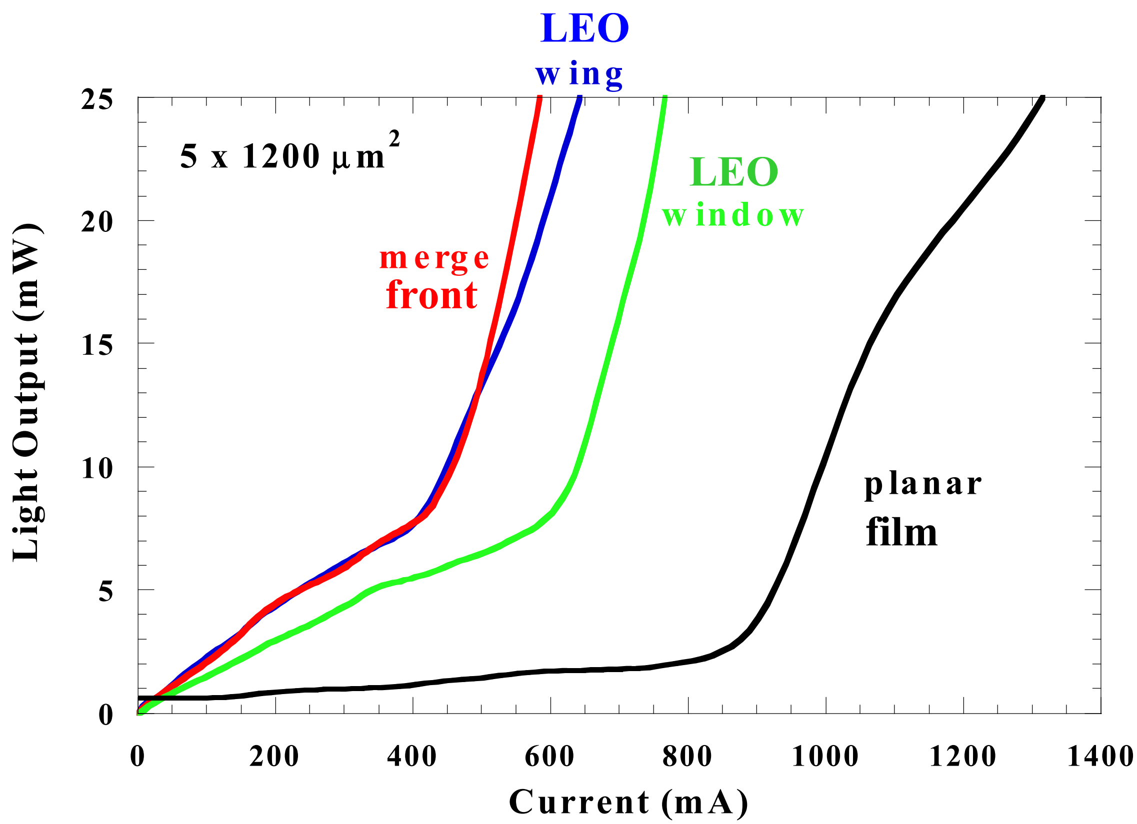
- Overgrown regions ('**wings**') have 3-4 orders of magnitude lower dislocation density than seed layer:



cross-sectional transmission electron micrograph

A: substrate
B: seed (planar) layer
C: mask (*e.g.* SiO_2)
D: '**window**' region
E: '**wing**' region

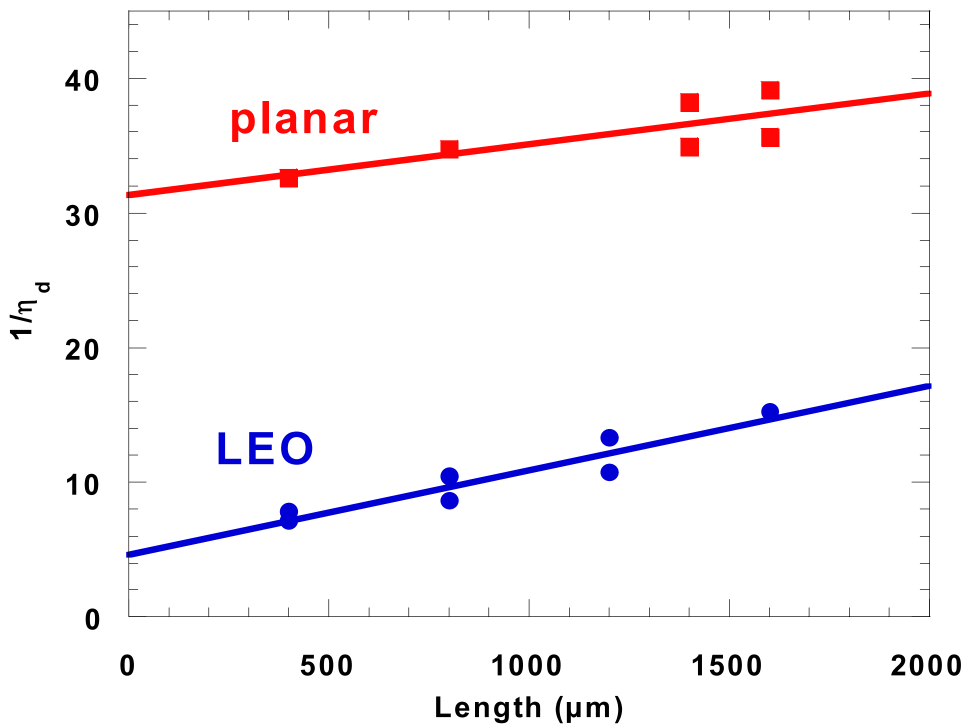
InGaN/GaN MQW Lasers on LEO GaN



- Reduction in threshold current density for lasers on 'wings' and coalescence fronts (from 8 to <4 kA/cm²)

InGaN/GaN MQW Lasers on LEO GaN (cont.)

- Lasers on LEO GaN have higher differential efficiency, and therefore higher internal efficiency



$$\eta_d = \eta_i \frac{\alpha_m}{\langle \alpha_i \rangle + \alpha_m}$$

As $\eta_d \uparrow$, $\eta_i \uparrow$

⟶ Lasers on LEO GaN have a internal efficiency of ~**22**%, compared to ~**3**% for lasers on sapphire

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